Lower Jurassic (Hettangian–Pliensbachian) microfossil biostratigraphy of the Ballinlea-1 well, Rathlin Basin, Northern Ireland, United Kingdom

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Abstract

The thickest section of Early Jurassic strata known from onshore Ireland (total Jurassic thickness 566 m) is reported from the Ballinlea-1 well (Rathlin Basin) on the north coast of Northern Ireland. A detailed biostratigraphical and palaeoenvironmental assessment is presented for this section largely based on calcareous benthic microfossils (foraminifera and ostracods). The Early Jurassic Waterloo Mudstone Formation (Lias Group) of Northern Ireland has previously received little micropalaeontological attention, therefore this work provides an opportunity to enhance palaeogeographic and palaeoenvironmental understanding for the Early Jurassic of the province, and this paper illustrates key microfossil taxa of this age from Ireland for the first time. The records, based on ditch-cuttings samples, demonstrate a stratigraphical range from Hettangian to Early Pliensbachian, consistent with other wells and boreholes in this basin. The assemblage compositions are comparable to those elsewhere in the European boreal Atlantic realm. Hettangian to earliest Sinemurian microfossil assemblages are generally of low diversity and are numerically dominated by metacopid ostracods with occasional influxes of foraminifera. Gradually, foraminiferal abundance (often dominated by species of the Lagenida) come to exceed those of the ostracods in the Early Sinemurian reaching greatest diversity in the Late Sinemurian. The sediments are considered to represent an inner to mid-shelf environment throughout while the record thickness for this region indicates ongoing syn-sedimentary fault movement along the basin margins throughout this period.

KEYWORDS: Ostracoda, foraminifera, Waterloo Mudstone Formation, Hettangian, Sinemurian, Pliensbachian.

Introduction and Geological Setting

Exposures of Early Jurassic sediments in Northern Ireland are relatively rare and are largely restricted to small (a few 10s of metres at most) coastal exposures (Figure 1). They often sit below cliffs of Late Cretaceous chalk (the Ulster White Limestone Group) and Paleogene basalts of the Antrim Lava Group (Mitchell, 2004). The exposures are discontinuous, faulted and their weakly consolidated nature makes them prone to landslip. Subsurface records of latest Triassic and Early Jurassic sediments are known from a number of boreholes and industrial wells but this paper deals with the thickest sequence of Early Jurassic sediments known from onshore Ireland, recovered from the Ballinlea-1 exploration well in the Rathlin Basin on the north coast of Ireland.

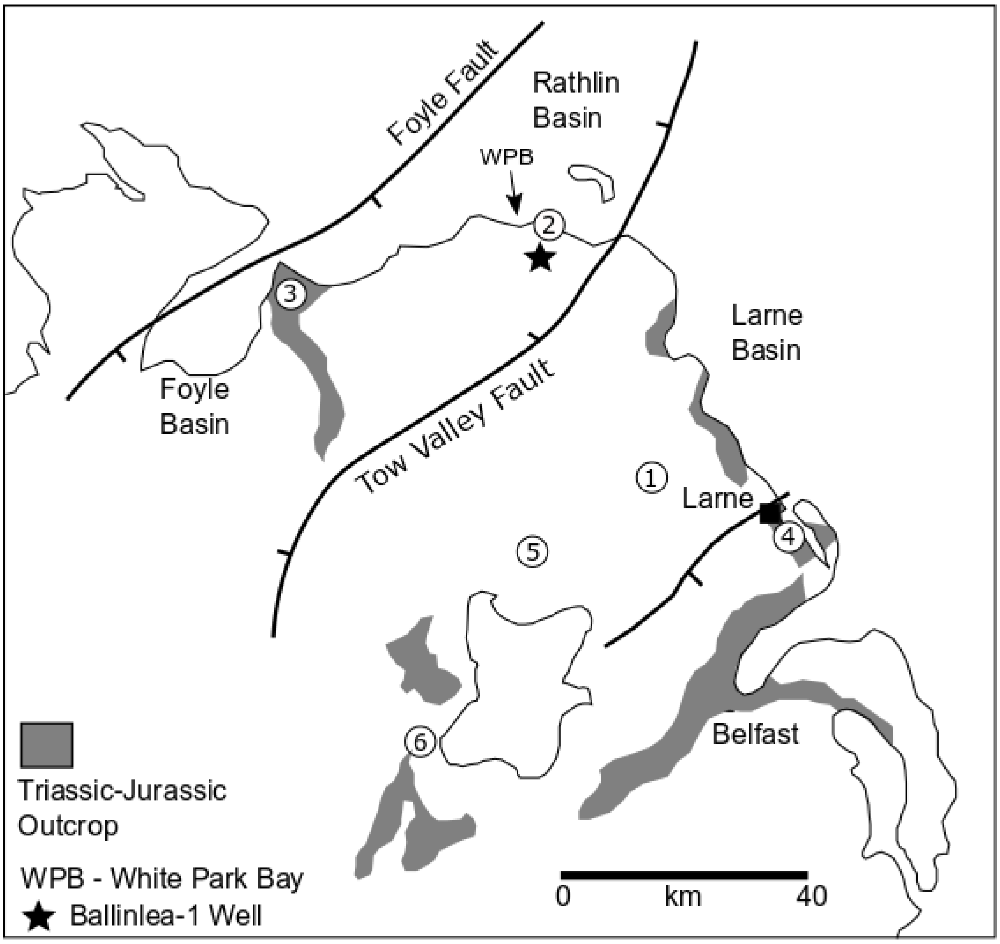


Figure 1. *Distribution of Triassic and Jurassic sediments in Northern Ireland, together with location of the main sedimentary basins, bounding faults and locations referred to in this work (1. Ballytober-1 well, 2. Port More Borehole, 3. Magilligan Borehole, 4. Larne-1 and Larne-2 boreholes, 5. Ballymacilroy Borehole, 6. Mire House Borehole). The map is modified from George (1967), Warrington (1997) and Middleton et al. (2001).*

Largely continuous records across the latest Triassic to earliest Jurassic interval are known from the region. Simms and Jeram (2007) summarised the occurrence of Late Triassic sediments in the Larne Basin at Waterloo Bay, noting that red-beds of the Mercia Mudstone Group were overlain by siltstones of the Collin Glen Formation (both Norian) and those are, in turn, disconformably overlain by Rhaetian sediments of the Penarth Group, divided into a lower Westbury Formation and an upper Lilstock Formation (Mitchell, 2004). Although there is evidence from across Northern Ireland to suggest that this succession of lithostratigraphic units occurs across many parts of the province (Raine et al., a this volume), Late Triassic outcrops have not been recorded within the Rathlin Basin and neither are sediments of this age proven with any certainty from the Ballinlea-1 well.

A broadly conformable boundary between the Penarth Group and the Waterloo Mudstone Formation is also recorded subsurface at Magilligan to the west of the Ballinlea-1 well (Bazley et al., 1997) although this has not been proven at the Port More borehole due to the presence of an intrusive sill (Wilson & Manning, 1978). While the Triassic-Jurassic boundary interval is exposed at Larne (Simms and Jeram, 2007) and in the nearby Carnduff-1 and 2 boreholes (Boomer et al., 202Xa) by contrast, the Lias Group from the Ballytober-1 borehole (also located in the Larne Basin) unconformably overlies the Mercia Mudstone Group (Fynegold Petroleum, 1991), which is a comparable situation to that in the Ballinlea-1 well.

Early Jurassic sediments from Northern Ireland are assigned to the Waterloo Mudstone Formation (Lias Group) which is broadly equivalent to the Blue Lias Formation and part of the Charmouth Mudstone Formation of Great Britain. The most significant outcrops in Northern Ireland occur at Waterloo Bay, Larne (Simms and Jeram, 2007), previously a candidate GSSP (Global Stage Stratotype and Point) for the Triassic/Jurassic boundary, and at White Park Bay (Wilson and Manning, 1978; Mitchell, 2004), all other exposures are only of a few metres' thickness. While the majority of outcrops are of very earliest Jurassic (Hettangian to Early Sinemurian) age, the exposures at White Park Bay are of latest Sinemurian to Early Pliensbachian age.

Prior to the drilling of the Ballinlea-1 well, the thickest Early Jurassic successions onshore Ireland had been recorded in boreholes at Port More (270 m), Mire House (125 m), Magilligan (76.5 m), Ballymacilroy (86 m) and Larne-1 (51 m), the nearby Larne-2 borehole encountered Mercia

Mudstone Group at the surface (Figure 1). In the subsurface, the youngest known Early Jurassic sediments in Northern Ireland are of the Ibex Chronozone (Early Pliensbachian) in the Port More Borehole (Warrington, 1997), demonstrating that the Waterloo Mudstone Formation in the Rathlin Basin appears more complete than elsewhere in the province, and this may be a consequence of different structural histories in the different basins between the early Jurassic and mid-Cretaceous, the next youngest lithostratigraphic unit.

The Ballinlea-1 Well

The Ballinlea-1 well is located on the north Antrim coast (55° 11′ 22″ N; 6° 22′ 21″ W; Figure 1) about 7 km south west of Ballycastle. The Rathlin Basin developed due to the reactivation of pre-existing fault systems during the late Palaeozoic followed by early Mesozoic extensional movement related to rifting along the margins of Pangaea (McCaffrey and McCann, 1992; Johnston, 2004; Holdsworth *et al*., 2012). The Rathlin Basin trends broadly northeast-southwest, deepening southeastwards into the Tow Valley Fault (McCann, 1988) and extends northwards, offshore, between the Antrim coast and the Isle of Islay (western Scotland). The eastern extent of the basin is concealed under the Paleogene basalts of the Antrim Lava Group (Johnston, 2004).

Ballinlea-1 was drilled as a hydrocarbon exploration well, by Rathlin Energy and partner Mancal Energy in 2008, targeting a Palaeozoic structure. The section encountered represent the thickest gross section of Lower Jurassic sediments known from the onshore area of Ireland (604 m total; net thickness just 566 m due to a large Paleogene intrusion within the sequence). Substantially thicker successions are known, however, from offshore the Republic of Ireland, for instance in the North Celtic Sea Basin, where around 2000 m of Lias Group sediments are proven in well sections (Copestake and Johnson, 2014; Raine et al., this volume) and in the Slyne Basin, offshore west of Ireland (Trueblood, 1992). The Jurassic sediments in the Ballinlea-1 well occur unconformably beneath a relatively thin cover (15 m) of Cretaceous chalk of the Ulster White Limestone Group, above which lies 92 m of Paleogene Antrim Lava Group (Figure 2). Above the studied section there is a further sequence of mudstones and recrystallized chalk associated with intrusive dolerite, this has been interpreted as a faulted repetition of sediments belonging to the uppermost Waterloo Mudstone Formation and lowermost Ulster White Limestone Group, presumably related to Paleogene volcanism. The Early Jurassic Waterloo Mudstone Formation principally comprises grey, calcareous mudstones with occasional thin grey limestones and silty mudstones. The succession is intruded by a Paleogene dolerite sill between 630-668 m. This study focuses on the largely continuous Early Jurassic succession from 343 m to 947 m measured depth below KB (kelly bushing), all depths are given relative to KB.

Riding (2010) undertook a preliminary age assessment of this well based on the presence and changing relative abundance of palynomorphs and some of those findings are incorporated into the age assessment below. At the time of drilling, the operator, Rathlin Energy, commissioned a biostratigraphic study of the Carboniferous succession in the Ballinlea-1 well, however, no biostratigraphic analysis was carried out on the Lower Jurassic section, which lay above the prospective target interval of the well.

In order to provide a more detailed stratigraphic and palaeoenvironmental interpretation of this well using calcareous microfossils, a total of 120 ditch-cuttings samples (from 255m – 980 m), at approximately 5 m intervals, were provided by the Geological Survey of Northern Ireland (GSNI). Seventy of these samples were processed using a combination of hydrogen peroxide method and multiple freeze-thaw cycles. Samples were studied at around 10 m spacing, though occasionally a 5 m spacing was used. Once processed, half, quarter or smaller residue splits, sufficient to provide 250–300 microfossil specimens where possible, were totally picked above 125 µm size fraction. Additional scans through the 63 µm fraction were undertaken to identify smaller species not encountered in the larger fractions. The residues contained various quantities of foraminifera, ostracods, micro-bivalves, micro-gastropods, echinoderm and ophiuroid fragments, while mica, pyrite, carbonaceous materials, iron nodules and quartz grains were distributed irregularly throughout.

Previous studies of Early Jurassic microfossils from Northern Ireland

Tate (1870) made the first published reference to Lias microfossils in Northern Ireland when he recorded the presence of *Dentalina obliqua* from the *'Lower Lias, Belemnite Shales'* of *'Island Magee'* (*sic*.). In the same volume, Wright (1870) referred to Tate's record and then listed a further twenty species of foraminifera from sediments at Ballintoy on the North Antrim Coast. A report in 1877 (Belfast Naturalists' Field Club) briefly noted additional Lias microfossil records from coastal outcrops in County Antrim. All these historical records referred foraminifera to incorrect, modern species names, however. Almost a century later, McGugan (1965) provided a brief checklist and drawings of some foraminifera (and noted the occurrence of at least three species of ostracods) that were recovered from inter-tidal exposures at White Park Bay. However, a number of errors in identification ultimately led him to suggest an erroneously old age of Angulata Chronozone (latest Hettangian) for these sediments, though that would have fitted with the age of most other coastal exposures in the province. Those exposures are now known to be of Late Sinemurian to Early Pliensbachian age (Simms and Murray, 202X; Boomer et al., 202Xb). The occurrence of both ostracods and foraminifera at Waterloo Bay was noted by Simms and Jeram (2007) from a single sample in the lowest part of the Waterloo Mudstone Formation. Copestake and Johnson (1989, 2014) also referenced the occurrence of foraminiferal marker taxa from outcrop samples from Northern Ireland held by Industrial service companies.

The geographically closest sections to be studied in any detail come from offshore the west coast of the Republic of Ireland (Ainsworth, 1990; Slyne and Erris basins), the Hebrides Basin, western Scotland (Ainsworth & Boomer, 2001) and the Llanbedr (Mochras Farm) Borehole of west Wales (Boomer, 1991; Copestake and Johnson, 2014) although these are all located in different depositional basins. Copestake and Johnson (1989, 2014) defined a foraminiferal biozonation scheme (JF biozones) that is applicable across north west Europe, and is tied to the standard ammonite chronostratigraphy. This foraminiferal biozonation scheme is applied in the current study to interpret the chronostratigraphic succession represented by the Waterloo Mudstone Formation penetrated in the Ballinlea-1 well.

Ballinlea-1 Early Jurassic microfossil biozonation biostratigraphy

More than species of 100 foraminifera (2 species of agglutinating, the remainder calcareous benthic) and more than 40 species of ostracods are recorded from this well, some of these records are of low abundance taxa and poorly preserved material. Most of the samples yielded microfaunal assemblages, but abundance was variable, some levels were barren, and the highest abundance observed was 46 microfossil specimens per gram of dry sediment.

As the material is entirely from ditch cuttings, the scheme is based on first down-hole occurrences (FDOs). Downhole caving can obscure last downhole occurrences and render such bioevents unreliable. Given the common occurrence and the generally well-preserved nature of the microfossil assemblages, the scheme here is considered to be relatively robust. The occurrence of the key marker species (foraminifera and ostracods) is shown against the lithostratigraphic succession in the well (Figure 2). Note that the interpreted age intervals given below, and as shown in Figure 2, are extended downwards to the top of the underlying interpreted age interval. The key microfossil marker taxa and some of the most abundant species are illustrated in figures 3 and 4. The intervals are dealt with from the top-down given that the samples in this well are ditch cuttings and therefore subject to caving (downhole contamination).

Partington *et al*. (1993) outlined a biozonation scheme (MJ zones) for the North Sea and onshore north west Europe that combined information from foraminifera and ostracods. There is currently a review of North Sea JF sequences in progress (Copestake & Partington, in prep.) and some of the information from that work is incorporated into the age interpretations below.

Interval 343 m-465 m; Early Pliensbachian.

The FDOs of the foraminiferal species *Vaginulinopsis denticulatacarinata* at 345 m, *Mesodentalina varians haeusleri* at 385 m, abundant *Brizalina liasica* at 400 m and *Paralingulina tenera subprismatica* at 410 m (which increases in numbers below 425 m) are indicative of the JF9 foraminiferal biozone (Copestake and Johnson, 2014), of Early Pliensbachian age. The presence of *V. denticulatacarinata* is particularly age diagnostic and this occurrence matches intervals within the Charmouth Mudstone of an equivalent age in eastern England (Lincolnshire) (see figured forms in Copestake & Johnson, 1989).

This interval includes the FDO of the ostracod species *Ogmoconchella danica* (410 m) which, together with *Ogmoconchella mouhersensis*, defines a Late Sinemurian to Early Pliensbachian ostracod zone in the Danish Embayment (Michelsen, 1975). Partington *et al*. (1993) described an MJ7a microfaunal subzone in the northern North Sea, characterised in part by the FDO of *O. danica*, that was ascribed by them an intra Early Pliensbachian age (Ibex to Jamesoni ammonite chronozone). However, *O. danica* has not previously been recorded younger than the Sinemurian at Mochras (Boomer, 1991), in the Hebrides (Ainsworth & Boomer, 2001) or on the Dorset Coast (Park, 1987). *O. danica* and *O. mouhersensis* have been found together in a number of samples from exposures of the Waterloo Mudstone Formation in the intertidal zone of White Park Bay, about 6 km north of the Ballinlea-1 well. Although those outcrops range in age from latest Sinemurian to earliest Pliensbachian based on Ammonite collections (Simms & Murray, 202X), it has not been possible to establish with certainty, a precise age of the samples from which those assemblages were recovered.

Riding's (2010) study of palynomorphs from Ballinlea-1 determined the interval 355 – 500 m to be Pliensbachian due to the dominance of bisaccate pollen and the miospore *Perinopollenites elatoides* which distinguished it from the lower samples of the well which were dominated by *Classopollis.* Riding's sampling interval was quite coarse, just 11 samples in total through the well with about 100 m resolution around the Late Sinemurian to Early Pliensbachian interval. However, his findings are not inconsistent with the microfossil-determined age.

In addition to the marker species noted above, the interval is characterised by the consistent and common presence of members of the *Marginulina prima* plexus, including *M. prima prima*, *M. prima spinata* and *M. prima interrupta*. Members of the *Paralingulina tenera* plexus are common to abundant, including *P. tenera pupa* and *P. tenera tenera* and *P. tenera tenuistriata*. Of particular note is the presence of *Reinholdella macfadyeni* at and below 415 m, becoming common at 450 m. This species is more typical of the Toarcian in onshore British and offshore Ireland successions, but is known from pre-Toarcian intervals in some parts of the United Kingdom, including the Yorkshire coast area, where it ranges as old as the Turneri Chronzone (Early Sinemurian) (Copestake et al., 2019).

The interval also contains *Nodosaria issleri*, which appears at 400 m and below. This species has been described as a Late Sinemurian restricted taxon (see discussion in Copestake and Johnson, 2014) and its occurrence in Ballinlea-1 in this interval is at odds with the Early Pliensbachian interpretation outlined here on the basis of the assemblage discussed above. An alternative interpretation, that the section is of Late Sinemurian age from 400 m, is possible but cannot be unequivocally substantiated.

Interval 480 m-685 m; Late Sinemurian

The FDO of common *Mesodentalina matutina* at and below 480 m is considered to mark the top of the Upper Sinemurian, based on the known distribution of this species from onshore and offshore UK successions (see Copestake and Johnson, 1989, 2014). This interval, down to the top of the underlying biozone, represents the JF7 to JF8 biozones of the latter authors. The increase in *Astacolus speciosus* at 570 m is further diagnostic of this interpreted age and biozone.

The presence of a probable specimen of *Reinholdella margarita margarita* at 550 m, if correctly attributed, marks the top of the JF6 biozone that equates with the Obtusum Chronozone, of intra Late Sinemurian age.

Interval 685 m-855 m; Early Sinemurian

The FDO of *Astacolus semireticulatus* at 685 m indicates an Early Sinemurian age, and the JF5 foraminiferal biozone at this depth. This species extinction is in the Turneri Zone (Copestake & Johnson, 2014). The FDO of *Marginulina prima incisa* is also recorded at this depth. This species is long ranging (Hettangian-Pliensbachian), however, it only consistently occurs as high as the Semicostatum Chronozone (Copestake and Johnson, 2014).

The FDO of *Neobulimina bangae* at 710 m, which becomes common at 715 m and abundant at 720 m is further confirmation of the Early Sinemurian, and the lower part of the JF5 biozone. This species becomes common in the Semicostatum Chronozone across its area of distribution and this chronozone can therefore be inferred to be present from 715 m. An increase in numbers of *A. semireticulatus* is observed at 720 m, which is further evidence for the presence of the Semicostatum Chronozone, given that this species occurs commonly in this chronozone (in the Sauzeanum Subchronozone) in the Mochras Borehole, in association with the increase in numbers of *N. bangae* (Copestake and Johnson, 2014).

The FDO of *Marginulina prima insignis* (common) at 730 m is notable. This subspecies ranges as high as the Pliensbachian, however, its peak abundance occurs in the Bucklandi Chronozone, as in the Hebrides Basin and at Mochras (Copestake and Johnson, 2014). This bioevent is interpreted to mark the top of the intra Early Sinemurian JF4 foraminiferal biozone at Ballinlea, which is confirmed by the restriction of *N. bangae* to the section above this level (this species ranges no older than the Bucklandi Chronozone.

The FDO of the ostracod *Ogmoconcha hagenowi* is also observed at 730 m. The FDO of *O. hagenowi* occurs within the Lower Sinemurian in onshore successions from the UK, within the Bucklandi Chronozone, as in the Mochras Borehole (Boomer, 1991, at the top of the Rotiforme Subchronozone following zonal revision in Copestake and Johnson, 2014), the Yorkshire coast (Copestake *et al*., 2019) and elsewhere in the onshore area (Boomer and Ainsworth, 2009). The FDO of *Ogmoconchella aspinata* is recorded at 745 m, suggesting an association of the FDOs of the two species, as in the Mochras Borehole (Boomer, 1991). Here, this species also has its FDO in the Rotiforme Subchronozone of the Bucklandi Chronozone.

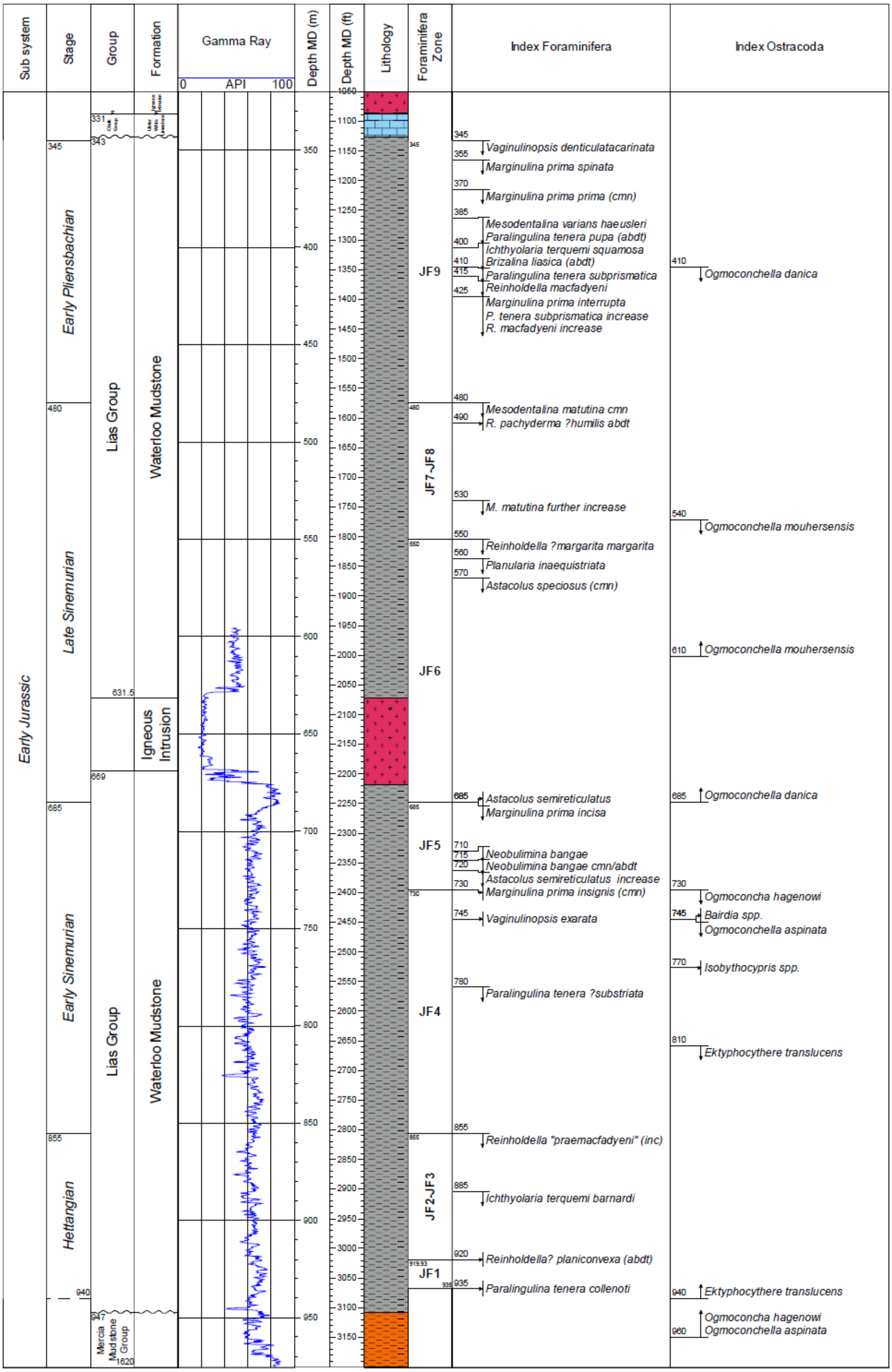
The FDO of the ostracod *Ektyphocythere translucens* occurs at 810 m. This species ranges from latest Triassic to Early Sinemurian in onshore UK sections (Boomer and Ainsworth, 2009). In Yorkshire, the species ranges as high as the Bucklandi Chronozone (Lord in Copestake *et al*., 2019), however in the Mochras Borehole the species upper range limit is in the upper Hettangian (Boomer, 1991). In the Larne Basin this species has a short range from Angulata Chronozone (latest Hettangian) to the base of the Bucklandi Chronozone (very earliest Sinemurian) (Boomer *et al*. 202Xa).

Interval 855 m-935 m; Hettangian

The FDO of *Reinholdella "praemacfadyeni"* at 855 m marks the top of the JF2 foraminiferal biozone, which is interpreted to indicate the upper limit of the Hettangian, the species is common at this depth, its informal name has been chosen to reflect its resemblance to the younger species, *R. macfadyeni*. *R. "praemacfadyeni"* was first noted in an exploration well in the South West Approaches, Melville Sub-basin (Well 73/1-1; Hooker et al., 1982) where it marks the top of the interpreted Hettangian, in association with the ostracod species *Kinkelinella medioreticulata*; both species are abundant at this level in the 73/1-1 well. *R*. "*praemacfadyeni*" is known from other sections, including the Southern North Sea (e.g. 48/22-1 well) in the interpreted Hettangian. It is restricted to the Hettangian to basal Sinemurian (Bucklandi Chronozone), as in the Yorkshire coast area (Copestake et al., 2019, as *R*. cf. *macfadyeni*). Its common occurrence appears to be restricted to the Hettangian.

The FDO of *Ichthyolaria terquemi barnardi* occurs at 885 m, the species is Hettangian restricted and is a marker for the JF2 biozone (Copestake & Johnson, 2014). The flood abundance of *Reinholdella*? *planiconvexa* occurs at 920 m. This abundance level is known from onshore UK in the mid to lower part of the Hettangian over the Planorbis Chronozone, Johnstoni Subchronozone to Liasicus Chronozone, Portlocki Subchronozone interval, within the JF2 foraminiferal biozone (Copestake & Johnson, 2014).

The occurrence of *Paralingulina tenera collenoti* at 935 m indicates an age within the range of late Rhaetian (Triassic) to Hettangian. In view of the absence of sediments that may be unequivocally



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316 **Figure 2**. *Lias Group stratigraphic succession and key microfossil bioevents, Ballinlea-1*.

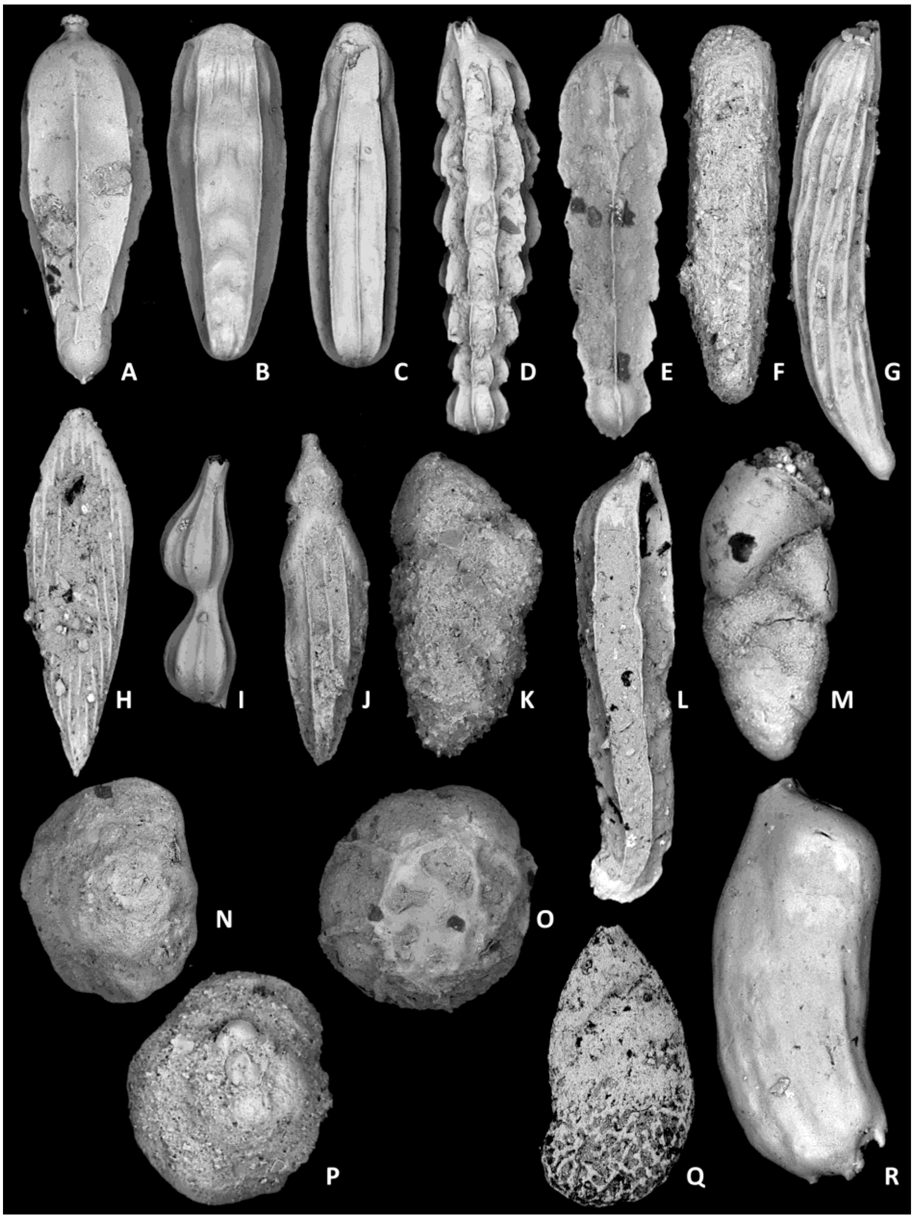

Figure 3. **Ballinlea-1 key foraminiferal taxa**. A. *Nodosaria issleri*, 400 m, (BU 5501), 200 µm long. B. *Paralingulina tenera tenera*, 845 m, (BU 5502), 200 µm long. C. *Paralingulina tenera subprismatica*, 520 m, (BU 5503), 200 µm long. D. *Marginulina prima interrupta*, 520 m, (BU 5504), 200 µm long. D. *Marginulina prima spinata*, 570 m, (BU 5505), 200 µm long. F. *Paralingulina tenera collenoti*, 935 m, (BU 5506), 200 µm long. G. *Mesodentalina matutina*, 475 m, (BU 5507), 200 µm long. H. *Ichthyolaria terquemi squamosa*, 490 m, (BU 5508), 200 µm long. I. *Mesodentalina varians haeusleri*, 530 m, (BU 5509), 200 µm long. J. *Ichthyolaria terquemi barnardi*, 885 m, (BU 5510), 200 µm long. K. *Neobulimina bangae*, 885 m, (BU 5511), 200 µm long. L. *Marginulina prima incisa*, 685 m, (BU 5512), 200 µm long. M. *Brizalina liasica*, 410 m, (BU 5513), 200 µm long. N. *Reinholdella "praemacfadyeni"*, 855 m, (BU 5514), 200 µm long. O. *Reinholdella macfadyeni*, 430 m, (BU 5515), 200 µm long. P. *Reinholdella? planiconvexa*, 920 m, (BU 5516), 200 µm long. Q. *Astacolus semireticulatus*, 720 m, (BU 5517), 200 µm long. R. *Vaginulinopsis denticulatacarinata*, 425 m, (BU 55018), 200 µm long.

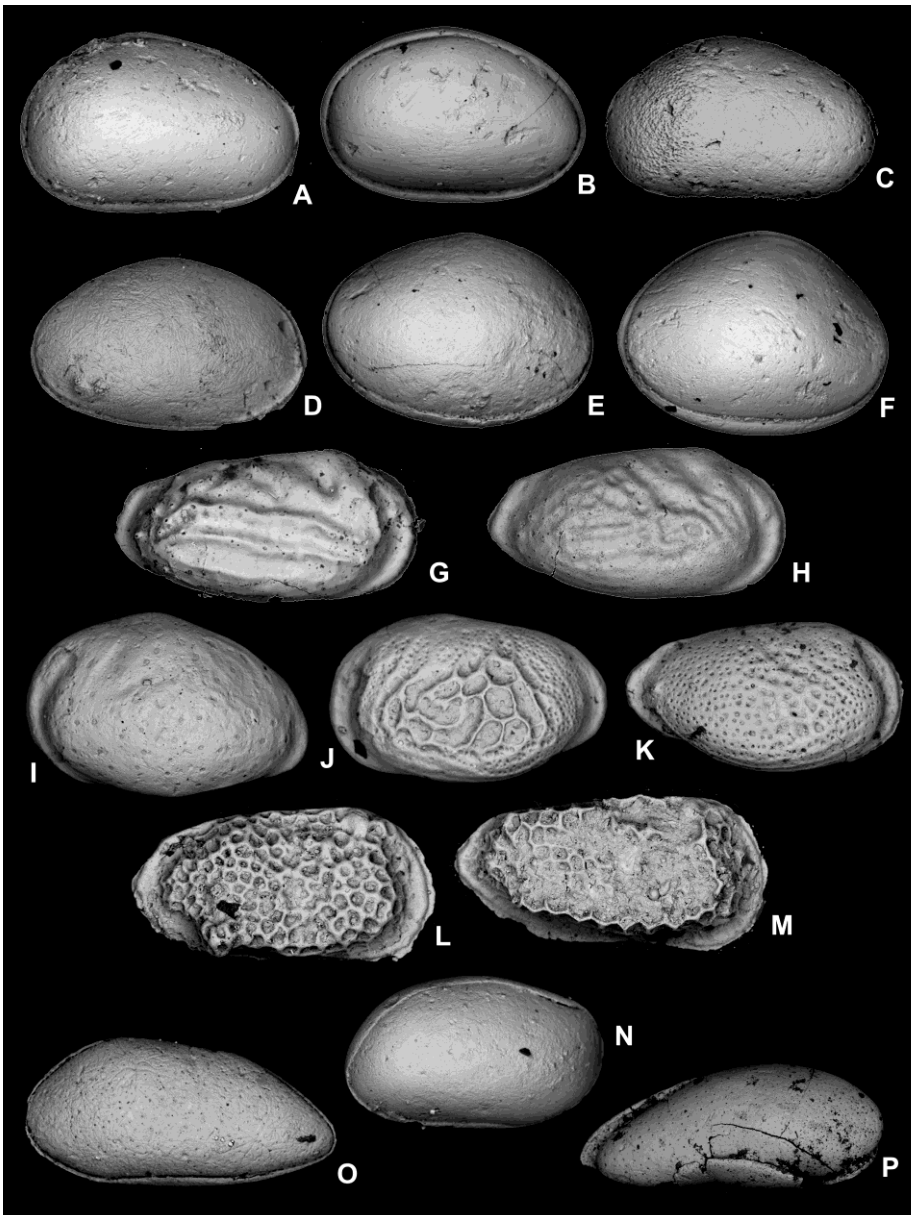

Figure 4. *Ballinlea-1 key ostracod taxa*. A. *Ogmoconchella aspinata* 920 m, (BU 5519), 200 µm long. B. *Ogmoconchella danica* 490 m, (BU 5520), 200 µm long. C. *Ogmoconchella mouhersensis* 540 m, (BU 5521), 200 µm long. D. *Ogmoconchella aequalis* 490 m, (BU 5522), 200 µm long. E. *Ogmoconcha* cf. *O. eocontractula* 510 m, (BU 5523), 200 µm long. F. *Ogmoconcha hagenowi* 800 m, (BU 5524), 200 µm long. G. *Pleurifera harpa* 400 m, (BU 5525), 200 µm long. H. *Pleurifera vermiculata* 490 m, (BU 5526), 200 µm long. I. *Ektyphocythere translucens* 845 m, (BU 5527), 200 µm long. J. *Ektyphocythere* sp. 845 m, (BU 5528), 200 µm long. K. *Gammacythere ubiquita* 410 m, (BU 5529), 200 µm long. L. *Eucytherura gassumensis* 845 m, (BU 5530), 200 µm long. M. *Eucytherura oeresundensis* 425 m, (BU 5531), 200 µm long. N. *Paracypris* sp. 425 m, (BU 5532), 200 µm long. O. *Isobythocypris* sp. 845 m, (BU 5533), 200 µm long. P. *Liasina lanceolata* 410 m, (BU 5534), 200 µm long.

assigned to the Penarth Group (uppermost Triassic) from the well (in which the LFO of *P. tenera collenoti* occurs in onshore UK sections; Copestake, 1989), the occurrence at 935 m is considered to mark the deepest indication of Hettangian age in the foraminiferal associations.

Riding (2010) determined the base of the Jurassic in this well as 945 m based on the presence of *Riccisporites tuberculatus* and the absence of distinctive Rhaetian markers such as *Rhaetipollis germanicus* and *Rhaetogonyaulax rhaetica*.

Although the lowest mudstone samples yielded greenish-grey and pinkish-grey sediment fragments, not unlike those of the latest Triassic Penarth Group in the Larne and Foyle basins, there is no unequivocal biostratigraphical microfossil or palynological evidence from the Ballinlea-1 samples to support such an age, the lowermost samples were barren of calcareous microfossils. It is therefore assumed that all of the mudstones recorded in Ballinlea-1 can be assigned to the Waterloo Mudstone Formation which is otherwise represented by medium-dark grey siltstones and claystones with subordinate limestones.

Faunal and Palaeoenvironmental summary

All of the sediments examined are considered to have been deposited in a relatively well-oxygenated, marine, inner shelf environment, (Based on the continued presence of benthic micro- and macrofossils throughout. Riding (2010) also concluded that the moderately-preserved, low diversity assemblages, which include acritarchs, pointed to deposition in an open marine setting throughout the Waterloo Mudstone Formation.

The changing abundances and diversity (as species richness) of both ostracods and foraminifera are shown in Figure 5. Throughout the Waterloo Mudstone Formation, the microfossil specimens are generally very well-preserved. Foraminiferal assemblages are dominated by the Order Lagenida but representatives of important accessory taxa assigned to the Miliolida, (Buliminida and families Ceratobuliminidae and Spirillinidae are also recorded. The foraminiferal assemblages are initially dominated by genus *Paralingulina*, followed, in decreasing abundance, (By *Lenticulina* and *Marginulina*, these latter genera dominate from the early Sinemurian onwards. The ostracod assemblages are numerically dominated by the Order Metacopina which are present in almost every sample, peaks in specimen abundance match very closely the abundance of Metacopina in a sample. There is an increasing abundance and diversity of the Order Podocopina recorded from the mid-part of the Early Sinemurian onwards.

Hettangian

Low abundances of benthic microfossils are noted during the very earliest Hettangian for both groups but then increase into the mid-late Hettangian, this pattern also seen elsewhere in Britain for the period. The peak in ostracod abundance in the late Hettangian is typically dominated by low-diversity assemblages of Metacopina, specifically *Ogmoconchella aspinata*. Broadly concomitant with that peak is a single, short lived influx of *Reinholdella? planiconvexa*. Despite this specific event in a single sample, ostracods are often numerically dominant in Hettangian to early Sinemurian assemblages across Europe (usually represented by two species, *O. aspinata* and *Ogmoconcha hagenowi*). These earliest Jurassic peaks in opportunistic taxa are also known from many other sections of the same age.

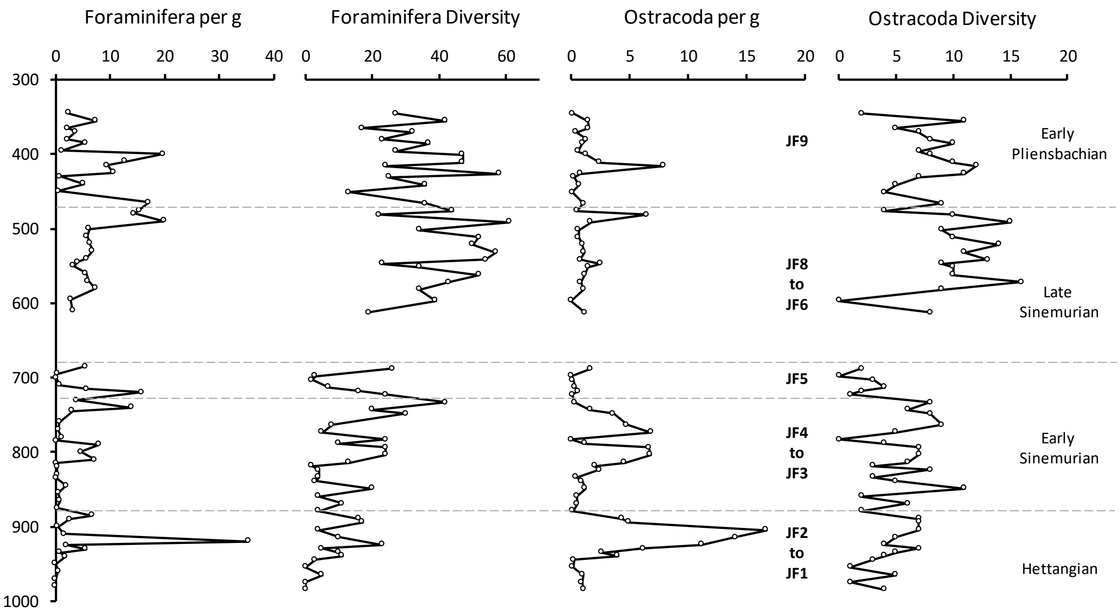

Figure 5. Changing diversity (species richness) and relative abundance (specimens per gram, dry sediment) for foraminifera and ostracods in Ballinlea-1 well, depth scale is in metres. The break in the record indicates the position of a Paleogene intrusion. JF zones after Copestake & Johnson (1989, 2014).

Early Sinemurian

Faunal turnover at 740 m sees the foraminifera become more diverse and numerically dominant over the ostracods for the first time, all later microfossil assemblages are numerically dominated by foraminifera.

Sediment residues between 820 m and 845 m yielded relatively abundant quartz grains with micro-ironstone nodules at 820 m. Intervals of early Sinemurian sandstone deposition are recorded 35 km to the west at Tircreven Burn (Mitchell, 2004; Raine *et al*. 202Xb) and it may be that the Ballinlea sediments represent a distal equivalent, possibly gravity flow deposits, that relate to sediment input from the west.

Between 615 and 675 m the core is intruded by Paleogene volcanics that resulted in limited contact metamorphism, making fossil extraction impossible on a handful of samples. There is no evidence for any significant stratigraphic break associated with the intrusion.

Late Sinemurian

The broad pattern of diversity (species richness) sees both groups peaking in the late Sinemurian (foraminifera 61 species, ostracods 16) and this could represent the establishment of stable mid-shelf conditions that succeeded shallower water environments in the earliest Jurassic. Hallam (1978) and Copestake and Johnson (2014) noted that the latest Sinemurian witnessed a major transgression in Europe. The assemblages in this period are dominated by *Paralingulina* with increasing abundance of *Lenticulina*, while ostracods continue to be dominated by the Metacopina.

Early Pliensbachian

The microfaunal assemblages remain diverse in the earliest Pliensbachian but record a slight decrease when compared to the late Sinemurian, the decline may be due to a minor fall of sea level during the earliest Pliensbachian.

Summary

The Ballinlea-1 well from North Antrim, Northern Ireland has yielded the longest sequence of Jurassic sediments known from onshore Ireland (both North and South). The cuttings samples available, yielded well-preserved and diverse assemblages of calcareous benthic microfossils (ostracods and foraminifera) that can be used to provide a chronostratigraphic age model and give insights into the depositional setting.

The biostratigraphic evidence indicates broadly continuous sedimentation from the earliest Hettangian through to the earliest Pliensbachian. Based on sedimentary and palaeontological evidence these early Jurassic sediments are considered to have been deposited in fully marine conditions with possible changes in water depth noted by broad changes in abundance and diversity. There is no clear evidence for any periods of dysaerobia in this section and this points to the northernmost part of Northern Ireland being a well-oxygenated, shallow shelf sea during the Early Jurassic.

Species richness in the Ballinlea-1 well is much higher than for the Hettangian to early Sinemurian interval than in both the Carnduff-1 (Boomer et al., 202Xa) and the Foyle Basin boreholes available to us (NIRE 05/08-0003; Raine et al., 202Xb). These differences may reflect a more stable, somewhat deeper-water shelf setting in the Rathlin Basin during this period when compared to the Foyle and Larne basins.

Acknowledgements:

The authors acknowledge the support of the Geological Survey of Northern Ireland for providing access to the Ballinlea material. Azrin Azmi acknowledges the financial support of Ministry of Higher Education Malaysia and the National University of Malaysia while undertaking a PhD at the University of Birmingham. The paper benefitted from the assistance of Mark Jeffs (MSci student, (Birmingham) and the advice of Michael Simms (National Museums Northern Ireland) and Nigel Ainsworth (Palaeodate) at various stages. Philip Copestake thanks Merlin Energy Resources Ltd for their support in undertaking this work.

Appendix A: Microfossil taxa author citations

Foraminifera

Astacolus semireticulatus Norling, 1968*; Astacolus speciosus* Terquem, 1858; *Ichthyolaria terquemi barnardi* Copestake and Johnson, 2014; *Ichthyolaria terquemi squamosa* (Terquem and Berthelin, 1875); *Marginulina prima incisa* Franke, 1936; *Marginulina prima insignis* (Franke, 1936); *Marginulina prima interrupta* Terquem, 1866; *Marginulina prima prima* d'Orbigny, 1849; *Marginulina prima spinata* Terquem, 1858; *Mesodentalina matutina* d'Orbigny, 1849; *Mesodentalina varians haeusleri* (Schick, 1903)*; Neobulimina bangae* Copestake and Johnson, 2014 (*Neobulimina* sp. 2 Bang, 1968); *Paralingulina tenera subprismatica* Franke, 1936; *Paralingulina tenera substriata* Nørvang, 1957; *Paralingulina tenera tenera* (Bornemann, 1854); *Reinholdella* cf. *macfadyeni* Copestake, Johnson, Lord and Miller, 2019 (= *R. "praemacfadyeni"* Hooker et al., 1985); *Reinholdella macfadyeni* Ten Dam, 1947; *Reinholdella margarita margarita* (Terquem, 1866); *Vaginulinopsis denticulatacarinata* Franke, 1936.

Ostracoda;

Ektyphocythere translucens (Blake, 1876); *Eucytherura oeresundensis* (Michelsen, 1975); *Eucytherura gassumensis* (Michelsen, 1975); *Gammacythere ubiquita* Malz and Lord, 1976; *Liasina lanceolata* (Apostolescu, 1959); *Ogmoconcha danica* Michelsen, 1975; *Ogmoconcha hagenowi* Drexler, 1958; *Ogmoconcha eocontractula* Park, 1984; *Ogmoconchella mouhersensis* (Apostolescu, 1959); *Ogmoconchella aspinata* Drexler, 1958 (= *O. ellipsoidea* Jones, 1872); *Ogmoconchella aequalis* Herrig, 1969; *Pleurifera vermiculata* (Apostolescu, 1959); *Pleurifera harpa* (Klingler and Neuweiler, 1959).

List of figures.

Figure 1. Distribution of Triassic and Jurassic sediments in Northern Ireland, together with location of the main sedimentary basins, (Bounding faults and locations referred to in this work (1. Ballytober-1 well, 2. Port More Borehole, 3. Magilligan Borehole, 4. Larne-1 and Larne-2 boreholes, 5. Ballymacilroy Borehole, 6. Mire House Borehole). The map is modified from George (1967), Warrington (1997) and Middleton et al. (2001).

Figure 2. Lias Group stratigraphic succession and key microfossil bioevents, (Ballinlea-1.

Figure 4. Ballinlea-1 key foraminiferal taxa

Figure 4. Ballinlea-1 key ostracod taxa

Figure 5. Changing diversity (species richness) and relative abundance (specimens per gram, dry sediment) for foraminifera and ostracods in Ballinlea-1 well, depth scale is in metres. The break in the record indicates the position of a Paleogene intrusion. JF zones after Copestake & Johnson (1989, 2014).

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